4.0. ELECTRO-OPTICAL SYSTEM TESTING

4.1. Introduction to Electro-Optical Theory

4.1.1. General

Figure 12 depicts the electromagnetic spectrum [Ref. 37:pp. 2.1a,2.82a]. The portion of the spectrum applicable to Electro-Optical (EO) systems lies between the Extremely High Frequency (EHF) band and the X-ray band [Ref. 37:p. 2.1]. EO systems are very similar in concept to their RF band counterparts including the radars discussed earlier; however, they have some unique strengths and weaknesses. Due to their extremely high frequencies and small wavelengths, the bandwidths of EO sensors are extremely high, and very narrow beamwidths are possible, providing highly accurate systems, capable of imaging. Narrow beam widths make EO systems hard to jam. [Ref. 37:p. 1.1].

Common applications of EO systems include [Ref. 37:p. 1.1] (Note that there is an RF counterpart to each application):

Threat Detection, Identification and Tracking
Threat Detection and Warning
Surveillance and Ground Mapping
Navigation
Communications
Weapons Delivery
Direct Radiation Weapons

For the purposes of demonstrating the thought process used for developing EO test techniques, this book will concentrate on passive systems, since these systems are perhaps the most unique of the EO category of avionics.

4.1.2.Infrared Systems

A large majority of EO systems operate in the near, middle and far InfraRed (IR) band. Additionally, the test techniques used to test IR systems are similar to the techniques used to test all EO systems. For these reasons, a sample IR system will be used to demonstrate the procedure used to develop all EO test techniques. The generalized thought process may then be applied to develop tests for specific systems.

All objects above a temperature of absolute zero emit within the IR bandwidth. The amount and frequency of the IR radiation emitted varies with the temperature of the object [Ref. 74:Chap. 3]. When operating, most military targets are strong IR emitters due to their high temperatures.[12] This is perhaps the greatest advantage of the IR EO system since it allows passive detection and imaging of militarily significant targets. [Ref. 37:p. 1.1]. The universal emittance of IR radiation also accounts for one of the most significant weaknesses of IR systems. Since all objects radiate IR at some level, a large amount of clutter exists in the IR environment from which the system has to discriminate the target. Another important disadvantage of IR systems is the strong level of atmospheric absorption and scattering of IR radiation. IR systems generally operate over much lesser ranges than RF systems due to this constraint. [Ref. 37:p. 1.2; Ref. 74:Chap. 4-5]. Finally, IR systems are strictly limited to line of sight propagation paths. [Ref. 37:pp. 1.1-1.2].

4.1.2.1. Discriminating Targets from Clutter

The discrimination of IR targets from background noise can be accomplished through a number of techniques. Wavelength/frequency (the frequency of the emitted radiation is dependent upon the emitting object's absolute temperature) can be used as a discriminator. This concept is known as chromatic filtering. [Ref. 37:p. 2.35; Ref. 74:p. 17.35-17.47, 22.95-22.10].

As illustrated in figure 3, the RF spectrum of a radar signal can be completely described in the amplitude versus frequency domain by breaking the spectrum into its Fourier components. The EO analogy is to break the IR or visual (or any other band) scene into Fourier components in the spatial fre-

[12]Some military targets can be purposely cold-soaked to make them harder to detect. For instance, a visually hidden tank can be shut off for days, making its temperature close to ambient. The tank can still be detected with a system which resolves the fine IR variations caused by differences in the heating/cooling rates of the steel tank versus the surrounding environment.

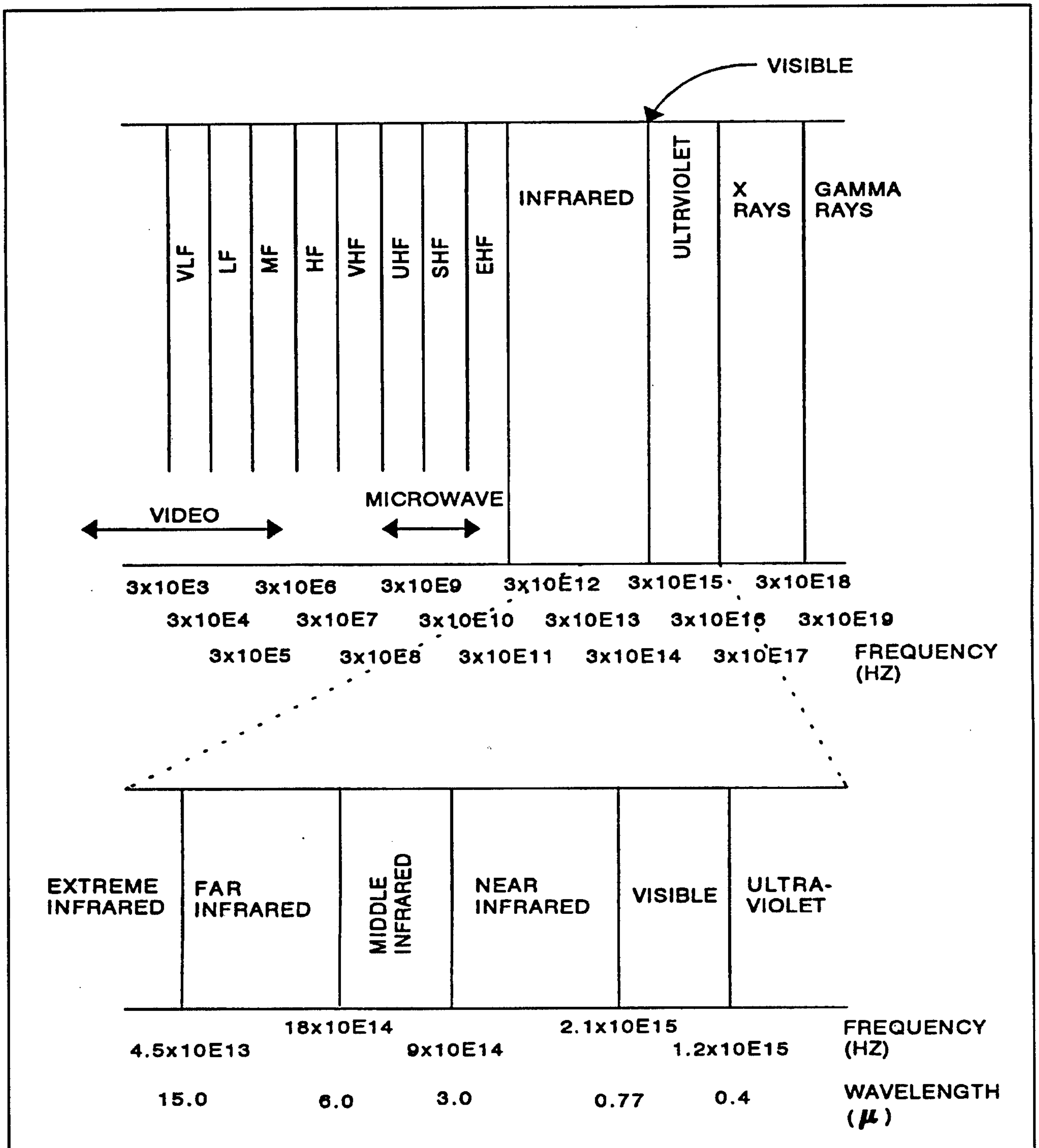

Figure 12: The Electromagnetic Spectrum [Ref. 37:pp.2.1a, 2.82a]

quency domain. Spatial frequency can be visualized as the number of times a component of a physical shape occurs over a unit of measurement. Normally, for EO systems, the units used are angular. As a simplistic example, a picket fence could be modeled with a single spatial frequency that describes the number of pickets per radian of scene. A tank, ship or series of objects, require a number of discrete Fourier components to be adequately described in the spatial frequency domain. The components can be filtered to eliminate unwanted features and thus the signal to noise characteristics of the sensor can be improved. Following filtering, the components are re-combined to present the filtered scene. [Ref. 37:pp. 2.36-2.39]. As an example of the application of the technique, an IR scene, including a ship, which is a fairly distributed source; and a flare, which approximates a point source, can be broken into its Fourier components. The flare would have a much higher spatial frequency, which could be filtered and eliminated by a low pass type filter. [Ref. 37:pp. 2.43-2.44]. The scene would then be re-combined to present the ship without the flare's presence.

When filtering in the spatial domain, (different than the spatial frequency domain) masks or reticles are used to optimize system response to targets of known dimensions. As an example, figure 13 [Ref. 37:pp. 2.42-2.43; Ref. 74:p. 17.11-17.25] depicts the response of a sensor with an Instantaneous Field Of View (IFOV) larger than, and then equal to the target. The IFOV is the angular width over which the sensor looks at any instant. In this simplified example, the system can only sense the total signal of all the emissions within the IFOV. As shown in the figure, the signal to noise ratio is highest when the IFOV matches the dimensions of the target. In this way, the signal to noise can be maximized for a target of known dimensions. [Ref. 37:pp. 2.42-2.43].

In optical time modulation, the incoming signal is time modulated in amplitude. The known modulation scheme can then be used to manipulate the signal during processing. The modulation can be provided through a number of techniques, including adding simple rotating mirrors or segmented reticles in the optical path. A typical application is in the elimination of internal noise. The signal is time modulated as it comes into the system at the reticle. Any added processing noise would not be modulated and could then be identified and filtered out.[Ref. 37:p. 2.45].

4.1.2.2. Image Scanning

In order to use powerful electronic processing devices, the IR scene must be modeled by an electrical signal. Additionally, IR sensors generally sense only the average intensity of the total IR scene within its IFOV. A larger scene is then constructed by sequentially sampling the IFOV of the sensor over the entire field of view and then combining the pieces. The sampling is usually performed at a given interval, providing direct conversion of the signal from the pure space/amplitude domain to the time/amplitude domain. The samples can then be manipulated by either digital or analog techniques using standard electronic processing devices. A simple sensor can be scanned in a grid fashion over the entire scene or a linear array can be scanned across one dimension of the scene to build the same picture. [Ref. 74:Chap. 17].

4.1.2.3. Infrared Atmospheric Transmittance

Figure 14 [Ref. 37:p. 2.10a] depicts the sea level transmittance of the atmosphere for the near to far IR band. The gaps in transmittance are due to absorption by resonant molecules such as water and carbon dioxide [Ref. 74:Chap. 5]. It is imperative that an operating wavelength for any IR detection system be chosen that falls within one of the "windows" of high transmittance. [Ref. 37:pp. 2.10-2.17]. This restriction can occasionally conflict with the desire for temporal filtering of military targets that have a maximum emittance within a gap of poor transmittance.

4.1.2.4. Radiation Detectors

Radiation detectors are at the heart of any IR system. Radiation detectors sense the average level of radiation within their IFOV and then convert this to an electrical signal. This facilitates the conversion of the spatial domain scene into the electrical time domain for further electrical/ electronic processing. The detectors can be used singly and scanned in two dimensions to build the entire "picture", used in a linear array and scanned in one dimension or used in a two dimensional array to build the picture without scanning [Ref. 74: Chap. 11]. In practice, single detectors and two dimensional arrays are rarely used. [Ref. 37: p. 2.52].

Radiation detectors are of two types. Thermal detectors absorb radiant energy and subsequently increase in temperature. Detection is performed by measuring the change of some property of the detection material resulting from the change in temperature. Common thermal detectors include [Ref. 74:p. 11.7; Ref. 37:p. 2.52]:

Pyroelectric
Thermopneumatic
Evaporagraphic
Thermovoltaic
Balometric

Photon detectors rely upon the direct effects of photons of radiant energy as

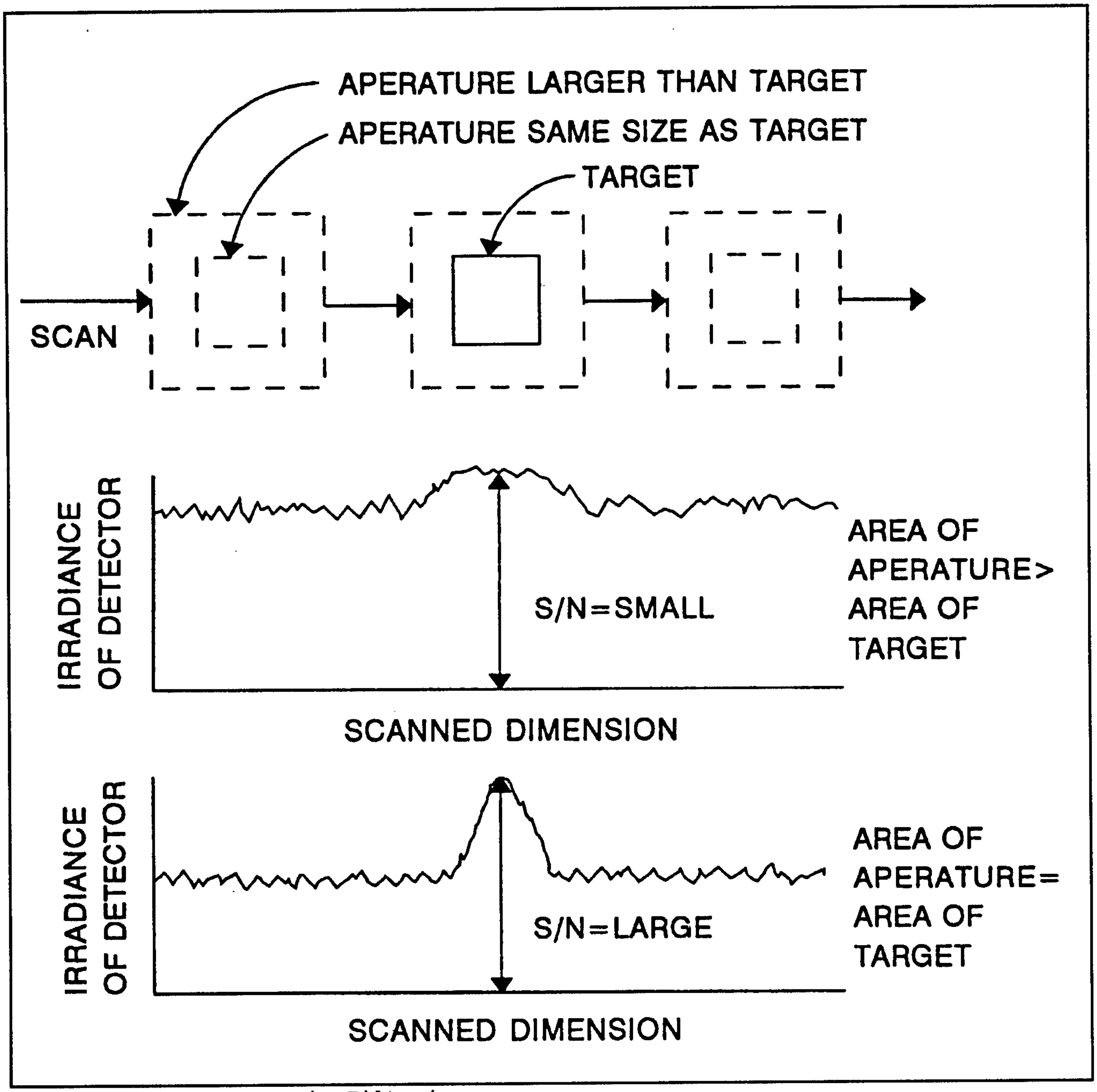

Figure 13: Space Domain Filtering

they react with the detector material. The effects are measured as an indication of the level of incident photons. [Ref. 37: p. 2.52]. Common photon detectors include [Ref. 37: p. 2.52; Ref. 74: p. 11.7]:

Photoemissive
Photoconductive
Photovoltaic
Photoelectomagnetic
Photographic

The signal to noise ratio of photon detectors is greatly increased when the detectors are cooled. Cooling as closely as possible to absolute zero reduces the amount of noise generated by the detector itself. Internally generated noise is indistinguishable in most cases from the received IR from the outside scene. Supercooling of the detectors greatly increases the performance of the detectors. Most IR detectors are cryogenically cooled using liquid gasses such as nitrogen or helium to temperatures around 4.2° to 77° K [Ref. 74: p. 15.6].

4.1.2.5. Forward Looking Infrared Radar

Figure 15 [Ref. 37:p. 2.9] depicts the IR, EO system to be used for development of the sample test techniques. This Forward Looking Infrared Radar (FLIR) is typical of many air to ground systems in operational use today. The conversion of incoming IR radiation from the external scene to a visible light representation occurs in three steps. First, the IR radiation is collected at the reticle and scanned onto the IR detectors. Next the detected IR scene is converted to the visual spectrum and scanned onto a television camera. Finally the visual spectrum output is converted by the television camera into a displayable format.

The IR radiation enters the FLIR through the reticle. The radar analogy of the reticle is the antenna. The sample reticle has two operating modes. In the Wide Field Of View (WFOV), the incident IR is unmagnified and is processed as a one to one representation of the outside world. In the Narrow Field Of View (NFOV) the incident radiation is magnified ten fold through a series of simple lenses.

The sample system uses a linear array of 186 IR detectors and so some method is required to scan the remaining dimension and build the two dimensional representation of the IR scene. This is facilitated by a rotating mirror. As the mirror rotates in the optical path, it reflects radiation onto the detectors proportional to the instantaneous level of incoming IR. Thus, the two dimensional IR scene becomes 186 analog signals. These 186 signals are then amplified and sent to 186 corresponding Light Emitting Diodes (LEDs) which emit light in the visible spectrum proportional to the incoming analog signal. Since the corresponding LED array is also linear, the visible light must be scanned identically to the IR scanning process to convert to a two dimensional representation. Perfect synchronization with the IR scanning process is required to insure a true visible spectrum representation of the IR scene. Perfect synchronization is insured by using a two sided mirror to scan the IR scene and using the back side of the mirror to simultaneously scan the LED generated scene. The visible spectrum scene is generated in two dimensions directly onto a video camera. The operator then views the scene generated by the camera as displayed on a cockpit CRT. The camera is necessary to provide the proper scan conversion from the analog visual display to the digital CRT display.

The scanning process described above determines the dimensions of the IFOV[13] of the sensor. The IFOV of the sample system is 15° horizontally by 10° vertically in the WFOV and 1.5° by 1° in the NFOV. The entire sensor is mounted in a three-dimensionally gimballed sphere, allowing the IFOV to be slewed through 200° left and right of the aircraft centerline and 20° up to 90° below the aircraft fuselage reference line. While slewing the sensor through the allowable limits, a portion of the IFOV at various gimbal positions is hidden by portions of the aircraft structure. The complete angular limits through which an object can be viewed through the FLIR exclusive of the areas masked by aircraft structure is the FLIR field of regard.

Two stabilization modes are available for the sample FLIR. In the fuselage stabilized mode the IFOV (the gimballed sphere) is held at selected angles as measured from the aircraft fuselage reference line. As the aircraft maneuvers, the IFOV center simultaneously moves as referenced to earth stabilized axes. Additionally, as the aircraft flies a groundtrack, the IFOV center translates along a groundtrack (assuming the FLIR is looking down) in a similar fashion. This stabilization mode is used when detection along the aircraft flight path is desired. Navigation FLIRs scan in this manner since it allows a real time update of the scene ahead of the flight path.

In the geographically stabilized mode, as the operator slews the FLIR to cover a desired scene, feedback from the aircraft INS is used to maintain the FLIR orientation relative to a fixed earth reference. The angles of orientation relative to the aircraft vary as the aircraft maneuvers. This stabilization mode has utility in targeting since it allows for viewing in

[13] The critical reader will note an inconsistency between the definition of IFOV used here and the definition provided earlier. By consensus, IFOV may be used to describe the angular limits of the scene projected upon the system detector array. Additionally, it is often used to describe the angular limits of the total scene covered by an imaging system with the reticle head fixed at one position. Typically, the reader must determine which definition is applicable by examination of the current context. The latter definition will be used subsequently in this book.

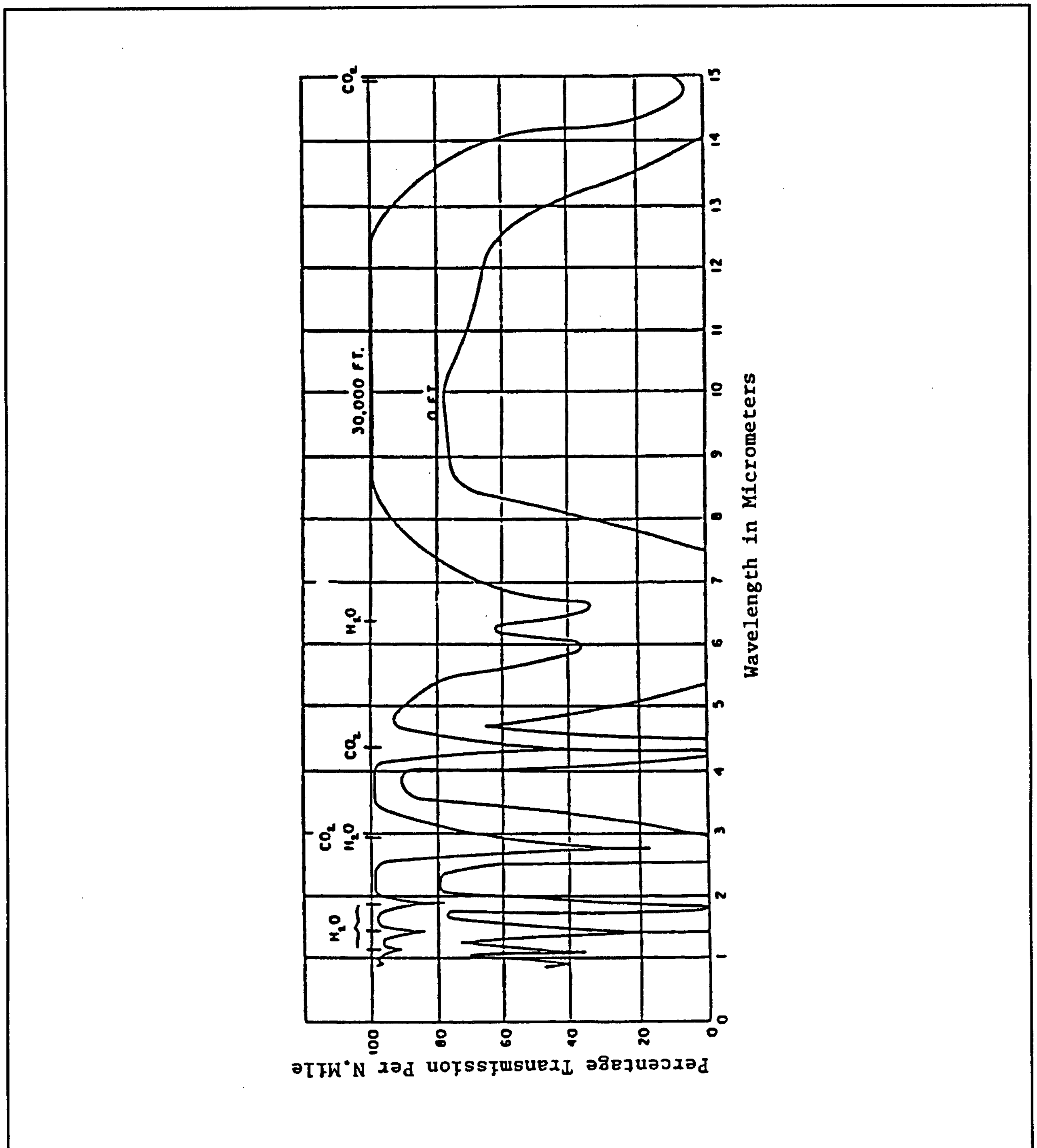

Figure 14: Infrared Atmospheric Transmittance at Sea Level [Ref.36:p.2.10a]

the direction of a target, even while maneuvering.

In most cases, the greatest source of stabilization errors for the geographically stabilized mode is the determination of the height of the aircraft above the point on the target where the FLIR crosshairs are placed. Often a manual input of target elevation is used or an assumption is made that the target is at sea level so that aircraft altitude from the navigation system can be used to partially stabilize the FLIR in three dimensions. Since an exact tapeline height above the target is not available, errors accrue and the crosshairs drift depending upon the accuracy of the approximations. Geographic stabilization is often

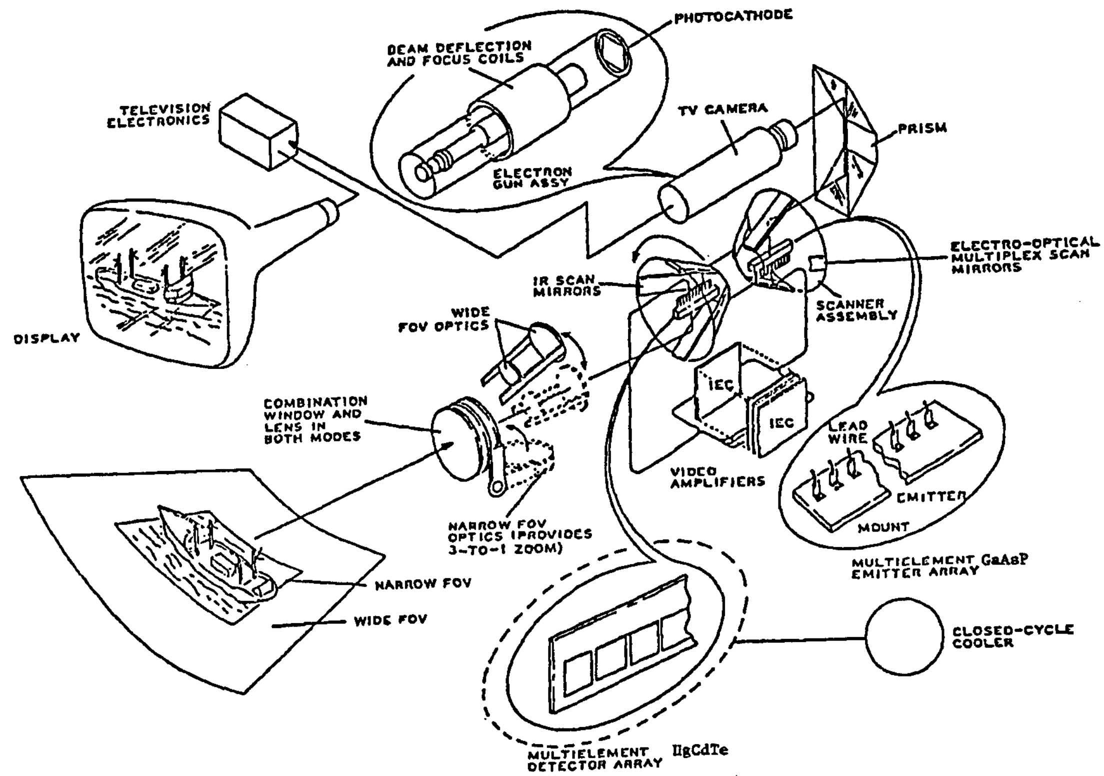

Figure 15: Sample Forward Looking Infrared Radar [Ref.37:p.2.9]

coupled with a ranging system such as radar or a Light Amplification through Stimulated Emission of Radiation (LASER) ranger. The range data is used to correct INS errors and enhance the stabilization of the FLIR on top of the target. The FLIR derived angles and radar or LASER derived ranges can also be used for targeting. Accurate angular measurement of the center of the FLIR IFOV and accurate alignment of the radar or LASER boresight with the FLIR is critical in these systems. For illustrative purposes, the sample system uses INS derived height above sea level as the default height above the target. The operator may manually enter a target height above sea level. When provided, target height is subtracted from the INS height to derive height above the target. No LASER range or coupled radar modes are available.

In most cases, FLIR displays are monochrome. Two options are available for display of the IR scene. Hot objects can be displayed as a lighter color against a darker, cool background (white hot) or as a darker color against a lighter, cool background (black hot). Hot objects are more precisely objects that emit larger amounts of IR radiation than their backgrounds. The utility of the two modes varies with the tactical situation and the type of target, and so most systems provide operator selection of the desired mode. The sample system used to develop the FLIR test procedures uses a CRT display. In addition to the FLIR video derived directly from the camera, several auxiliary display fields are multiplexed onto the CRT. The sample system provides a cross at the boresight center to facilitate centering the FLIR during targeting. Additionally, the horizontal angle from the aircraft centerline to the FLIR boresight is displayed along the bottom of the CRT and the vertical angle from the aircraft fuselage reference line to the FLIR boresight is displayed along the left side of the CRT.

With the exception of FLIRs set at fixed boresights, the operator must have some means to control the center of the FLIR IFOV. In the sample system, a joystick hand controller is used. The controller is used in three situations. In the fuselage referenced mode, the hand controller is used to adjust the boresight angle from the fuselage. In the geographically stabilized mode, the hand controller is used to center the FLIR over a geographic point that remains stabilized with reference to the earth angles excluding errors caused by the tapeline height above the target. After placing the FLIR crosshairs over the target of interest, the inertial feedback system maintains alignment on the target.

4.1.3. Electro-Optical System Human Factors

As in the radar human factors section, no attempt will be made to completely cover the topic of ergonomics[14]. As with radar systems testing, electro-optical systems testing must be performed while seated at the DEP and wearing a full set of personal flight equipment. The procedure for finding the DEP was explained in the radar theory section. The anthropometric measurements and flight gear worn by the evaluator must be recorded.

4.2. ELECTRO-OPTICAL SYSTEMS TEST TECHNIQUES

4.2.1. Preflight and Built in Tests

4.2.1.1. Purpose

The purpose of this test is to assess the suitability of the FLIR preflight and turn on procedure and the BIT to quickly and easily bring the FLIR on line and insure an operating system once airborne.

4.2.1.2. General

As airplanes become more expensive, fewer and fewer will be available to accomplish each mission, amplifying the loss of individual airplanes to inflight failures. Quick, accurate ground preflight tests are essential to determine system status while repairs can still be made. A quick response/alert time is also important and so these checks must be expeditious and must allow the operator to prepare for the mission with a minimum of distractions. Limited airplane availability also implies the need for quick turn arounds to send the same aircraft out for successive missions. This necessitates a very short preflight and turn on procedure that can be accomplished safely and thoroughly before a hurried combat mission. In the case of a FLIR, the time required for the cool down phase of the IR detectors is often the most time consuming portion of the turn on sequence; although, some very new systems use open loop coolers with much quicker cool-down times.

4.2.1.3. Instrumentation

A stop watch and data cards are required for this test. A voice tape recorder is optional.

4.2.1.4. Data Required

Record qualitative comments, time to complete the preflight/turn on and time to complete the BIT. A record of BIT indications is required. If a separate discrete is available announcing the completion of the cool down sequence, record the time to obtain this advisory.

4.2.1.5. Procedure

Perform a normal system turn on before each test flight using the published system check list. Note the times of FLIR cool down and time out and the total system preflight time up to the ready for operate indications. Perform a preflight BIT, noting the total BIT time and indications. Note any correlation between the BIT indications and the FLIR's operation. Perform a complete system check out of the failure indications while on the ground. Make qualitative comments as appropriate.

4.2.1.6. Data Analysis and Presentation

The time and complexity of the preflight procedures listed in the operator's

[14] Wolfe and Zissis provide a discussion of IR display issues [Ref. 31: Chap. 18]